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SUMMARY

Tubular stainless-steel targets armored with three types of internally reinforced beryllium were impacted with hypervelocity projectiles to determine the cratering behavior and the relative effectiveness of the reinforcements in reducing external cracking damage. The three methods used to internally reinforce the armor were compartmentation, concentric rings of mesh, and randomly oriented, uniformly dispersed filaments. A light-gas gun was used to accelerate 3/32-inch-diameter Pyrex spheres to a nominal impact velocity of 24 000 feet per second. The tubular beryllium targets were maintained at a temperature of 1300° F during impact.

Measurements of the craters, descriptions of the total damage, and photographs of the tubes are presented, and comparisons are made with previously reported damage to comparable homogeneous beryllium armored targets. Impacts on the reinforced-armor targets, which were heavier per unit length than the unreinforced-armor targets, showed little reduction in the external cracking damage in the armor compared with the unreinforced-armor targets.

INTRODUCTION

Beryllium has great appeal as an armor material to protect space radiators from the damage caused by meteoroid impact because of its theoretical ability to provide a given level of protection with the least weight. In addition, beryllium also has a high value of thermal conductivity, a necessary requirement in a space radiator material (refs. 1

and 2). Experiments have shown, however, that although the beryllium is very resistant to high-velocity penetration, it is very susceptible to damage in the form of cracking in the region of impact and in areas remote from the site of impact (refs. 3 and 4). In a series of high-velocity impact experiments using a variety of beryllium-armored tubes (ref. 4), the severity of damage to the beryllium armor was found to vary with the processing method of the armor material. The damage in all cases, however, had the same form, that is, large areas of front spall and cracking at great distances from the impact. The presence of the extensive cracking damage is undesirable since both the thermal conductivity in the armor and the load-carrying ability and structural integrity of each damaged radiator tube is reduced. Therefore, various means of containing or reducing the cracking damage in the beryllium armor were investigated.

Three methods of reinforcement were tested in this investigation. The first method involved compartmenting the beryllium armor into a lattice-type structure that was designed to limit the cracking damage to the area of each compartment. The second method used two concentric rings of wire mesh embedded in the beryllium armor. This configuration was designed to limit the cracking damage to the outer ring of armor and to retain the armor fragments around the tube. The third configuration employed bent-wire filaments interspersed uniformly throughout the beryllium armor in random orientation. This configuration was designed to provide mechanical reinforcement in the armor.

Reported herein are the results of hypervelocity impact into the three configurations of reinforced beryllium targets. The experiments were conducted at the General Motors Corporation, Defense Research Laboratories, Santa Barbara, California, under NASA Contract NAS 3-2798. A qualitative comparison of the damage is made between the reinforced targets and previously reported results on beryllium-armored tubes without reinforcements. The relative effectiveness of the reinforcements on the cracking damage is discussed.

EXPERIMENTAL PROGRAM

Light-Gas Gun Range

The experiments described herein consisted of impacting beryllium-armored tubes with small spherical projectiles at high velocities. The 3/32-inch-diameter Pyrex spheres were accelerated to a nominal impact velocity of 24 000 feet per second with the light-gas gun shown schematically in figure 1. The light-gas gun accelerates the projectile with hydrogen gas, which is compressed to high pressures by a piston that is driven by a high explosive. The 3/32-inch-diameter projectile is carried inside the 0.30-inch-inside-diameter launch tube in a plastic sabot that is removed by drag forces in the flight

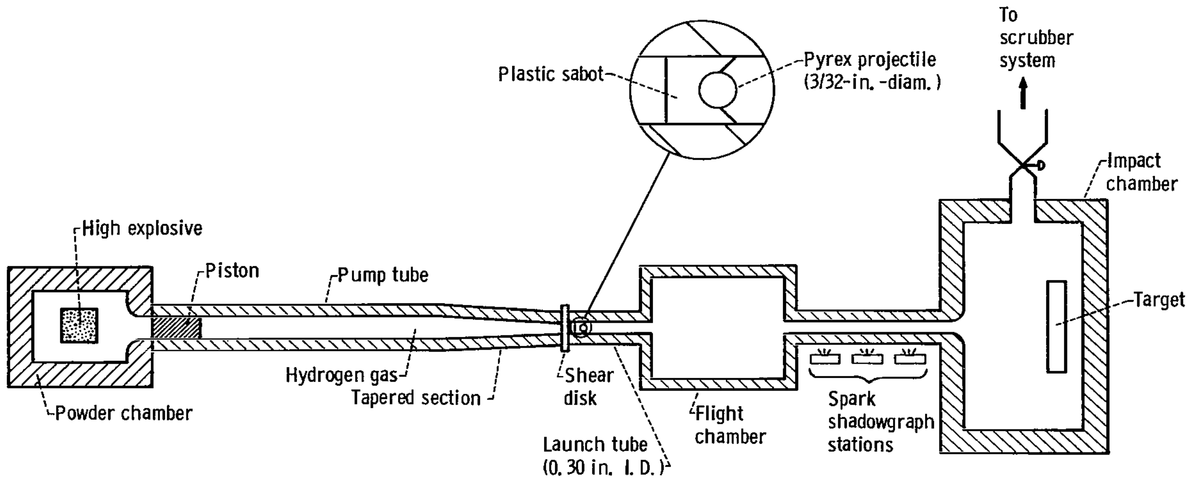


Figure 1. - Schematic diagram of light-gas gun.

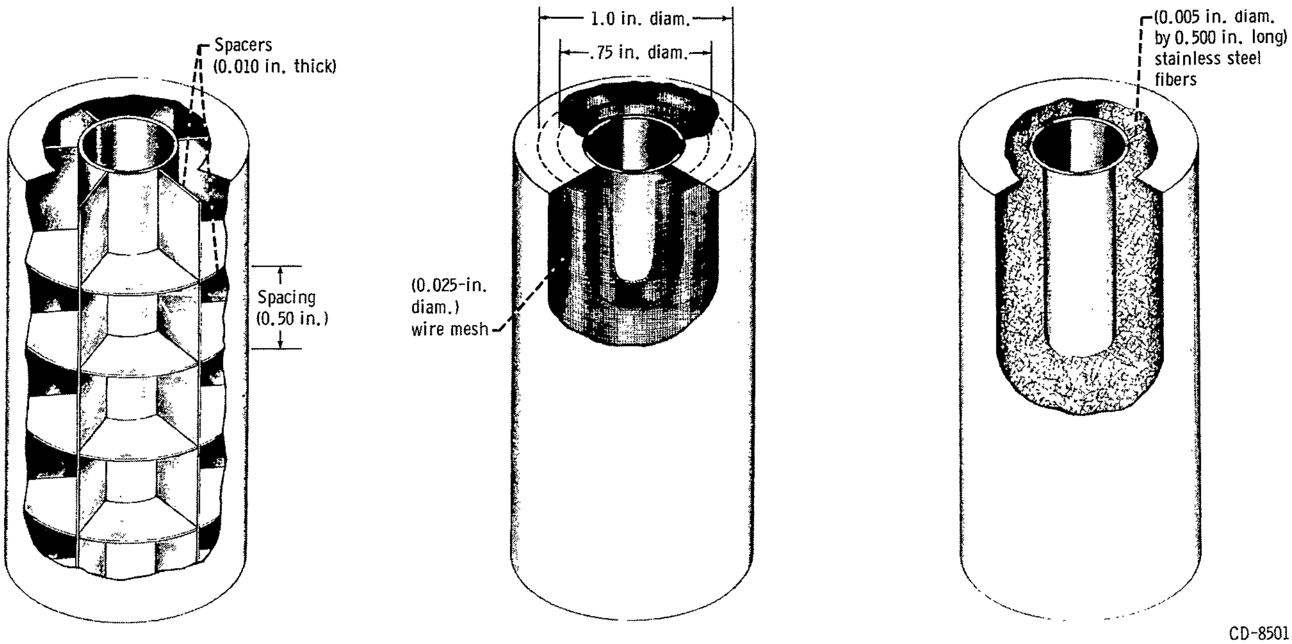
chamber during the flight of the projectile (fig. 1). The integrity of the projectile is monitored at the three spark shadowgraph stations shown in figure 1. The time of flight of the projectile between the spark stations is measured by electronic timers, which permit the computation of the projectile velocity. The accuracy of the velocity measured in this manner is estimated to be ±1 percent (refs. 4 and 5).

The target is mounted in an impact chamber, which in turn, is connected with an air-scrubber system. After impact, the entire range is exhausted through a filter system that provides safe conditions for the disposal of toxic materials such as beryllium (ref. 6). Prior to each impact test, the launch tube and target chamber were purged with helium gas, pumped to low pressures, and sealed from the pump tube by an aluminum shear disk (fig. 1). All the experiments described herein were conducted at a pressure of approximately 30 torr. A more detailed discussion on the features of the light-gas gun can be found in references 4 and 5.

Description of Targets

The impacted targets consisted of thin tubes of AISI 316 stainless-steel armored with beryllium that was reinforced with AISI 316 stainless-steel. All the tubular target liners had outside diameters of 0.50 inch and wall thicknesses of 0.028 inch, the target outside diameters were nominally 2.25 inches, and the beryllium armor thickness was nominally 0.363 inch.

The three reinforced beryllium armors are shown in figure 2. The first reinforcement was constructed by assembling 0.010-inch-thick stainless-steel spacers longitudinally and transversely around the liner tube to form a series of compartments at 0.5-inch intervals as shown in figure 2. Beryllium segments, cold pressed to size, were inserted



(a) Compartmented. (b) Mesh reinforced. (c) Fiber reinforced. (Fibers compose approximately 15 volume percent.)

Figure 2. - Beryllium hypervelocity impact targets reinforced with AISI 316 stainless steel. Target outside diameter, 2.25 inches; liner tube outside diameter 0.50 inches wall thickness, 0.028 inch; liner tube material AISI 316 stainless steel.

in the compartments, and the entire assembly was gas-pressure bonded. This target configuration was intended to restrict the cracking damage for a given impact to the small volume of the impacted compartment.

The second reinforcement consisted of stainless-steel wire mesh in two concentric shells imbedded in the armor around the liner as shown in figure 2. The mesh had 16- by 16-wires per inch, and the wire diameter was 0.025 inch. The diameter of the inner wire-mesh shell was about 0.75 inch, and the diameter of the outer wire-mesh shell was 1.0 inch. The beryllium powder was loaded through the mesh around the tube, hydrostatically pressed, and gas-pressure bonded. This target configuration was intended to limit the cracking damage to the outer layer of armor and to prevent dislodgement of the internal layers of armor.

The third reinforcement consisted of randomly oriented stainless-steel filaments interspersed uniformly throughout the beryllium armor as shown in figure 2. The filaments were fabricated from 0.005-inch-diameter wire cut to lengths of 0.50 inch and bent 90° at the center. The steel filaments and beryllium powder were packed around the stainless-steel liner tube, and the target assembly was gas-pressure bonded. After bonding, the stainless-steel filaments constituted approximately 15 volume percent of the beryllium armor. This target configuration was intended to retain mechanically the cracked

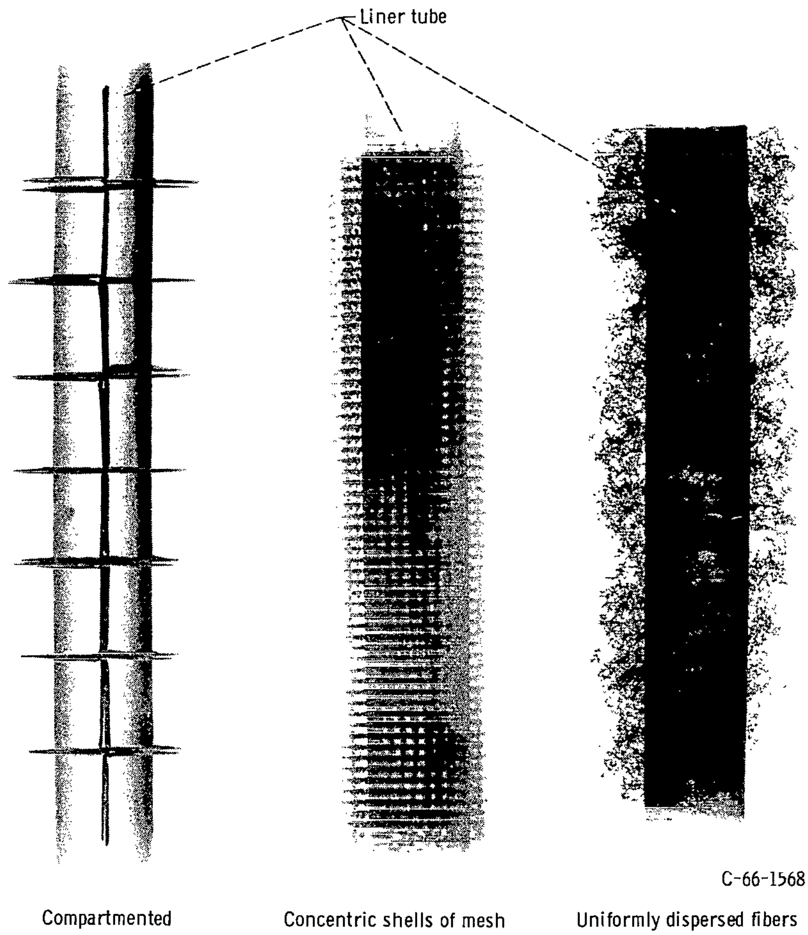


Figure 3. - X-ray prints of AISI 316 stainless-steel reinforcements in beryllium-armored tubes.

sections of armor. Further details of the fabrication processes and descriptions of the completed targets are given in reference 7.

Figure 3 shows X-rays of the completed targets and the position of the stainless-steel reinforcements. Only the stainless-steel reinforcements and liners are visible in figure 3 since beryllium is essentially transparent to X-rays.

Impact Tests

Each of the three reinforced configurations was impacted with a single projectile, and one additional fiber-reinforced target was impacted twice, thus a total of 5 impacts were performed in this investigation. The fiber-reinforced and the compartmented configurations were heated to 1300° F and impacted, but the mesh-reinforced target was inadvertenly heated to this temperature twice before the projectile impact occurred. As shown in figure 4, the measurements recorded for each impacted target were crater depth P, crater diameter, dimple height h, and impact angle λ.

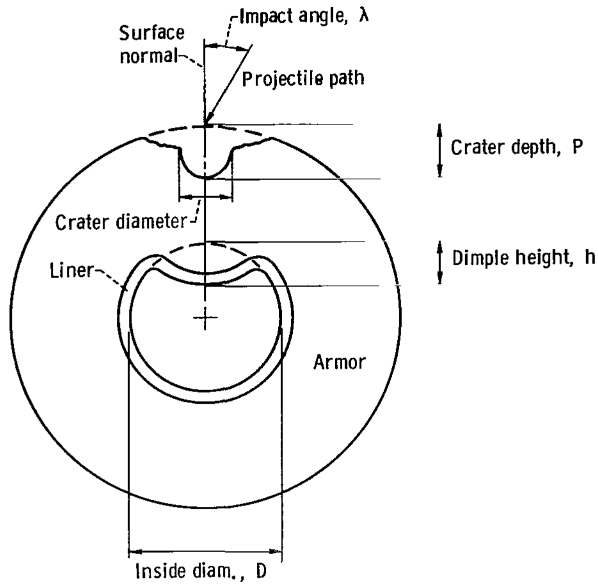


Figure 4. - Impact damage measurements.

TABLE I. - IMPACT DATA

[All impacts were made with 3/32-inch-diameter Pyrex spheres, and all target temperatures were 1300° F.]

Target	Armor description	Impact round number	Projectile		Impact angle, λ, deg	Measured penetration depth, P, in.	Crater diameter, in.	Dimple height, h, in.
			Mass, g	Velocity, ft/sec				
1	Compartmented	D-942	0.0177	24 200	12	0.177	0.21	0.107
2	Mesh reinforced	[a]D-1089	0.0184	23 600	12	0.184	0.22	0.112
3	Fiber reinforced	D-941	0.0177	24 000	22	0.173	Not measured	0.121
4	Fiber reinforced[b]	D-1090	0.0179	23 800	17	0.150	0.20	0.075
		D-1216	0.0181	23 500	2	0.179	0.21	0.108
5	Unreinforced (ref. 4)	D-416	0.0174	25 300	0	0.207	0.25	0.109
6	Unreinforced[b] (ref. 4)	D-1093	0.0180	24 000	55	0.162	0.20	0.112
		D-1094	0.0177	24 000	55	0.160	0.24	0.088

[a]Target heated to 1300° F twice before impact.

[b]Same target impacted twice.

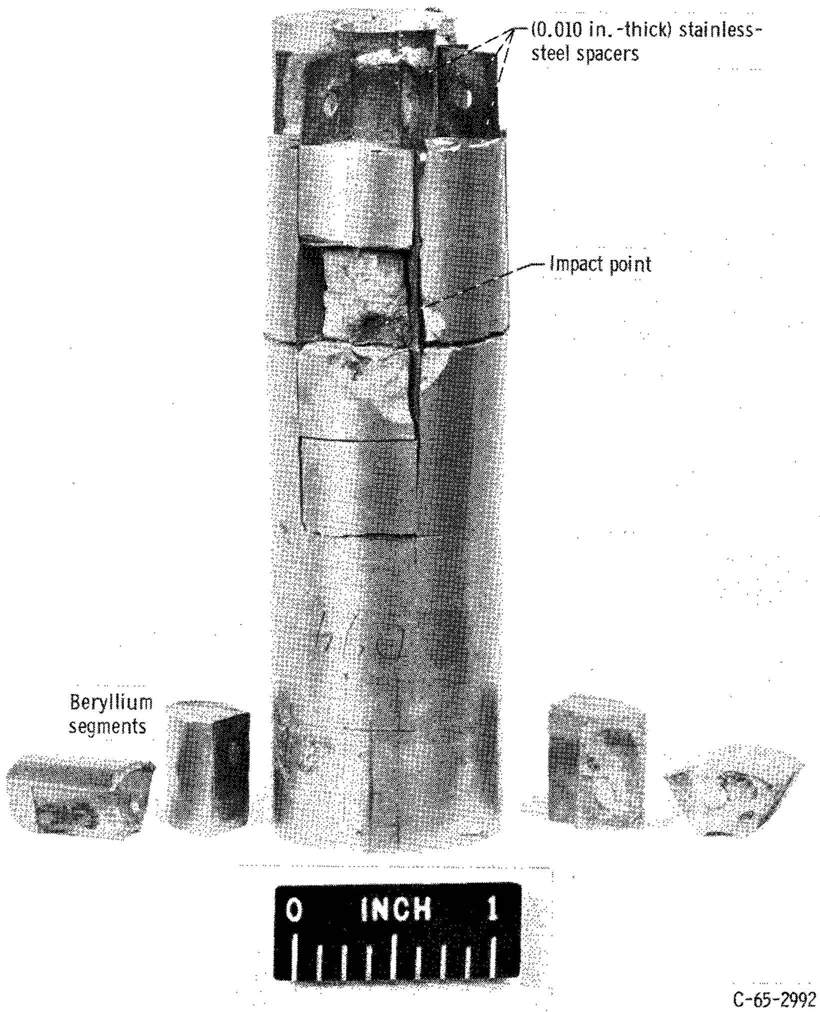


Figure 5. - Compartmented beryllium-armored tube after impact (target 1). Test conditions: projectile, 3/32-inch-diameter Pyrex sphere; impact velocity, 24 200 feet per second; target temperature, 1300° F.

RESULTS AND DISCUSSION

A complete tabulation of the test results is given in table I for the impact tests conducted in this investigation and for the results of a test into comparable, unreinforced beryllium targets reported originally in reference 4. Both targets from reference 4 (targets 5 and 6) had 0.50-inch-inside-diameter stainless-steel liners, but target 5 had a liner wall thickness of 0.020 inch and target 6 had a liner wall thickness of 0.010 inch. Listed in the table is a description of the targets impacted, the projectile mass, the velocity, the impact angle, the crater depth, the crater diameter, and the dimple height. The gross external damage was assessed from inspection and photographs of the impacted targets.

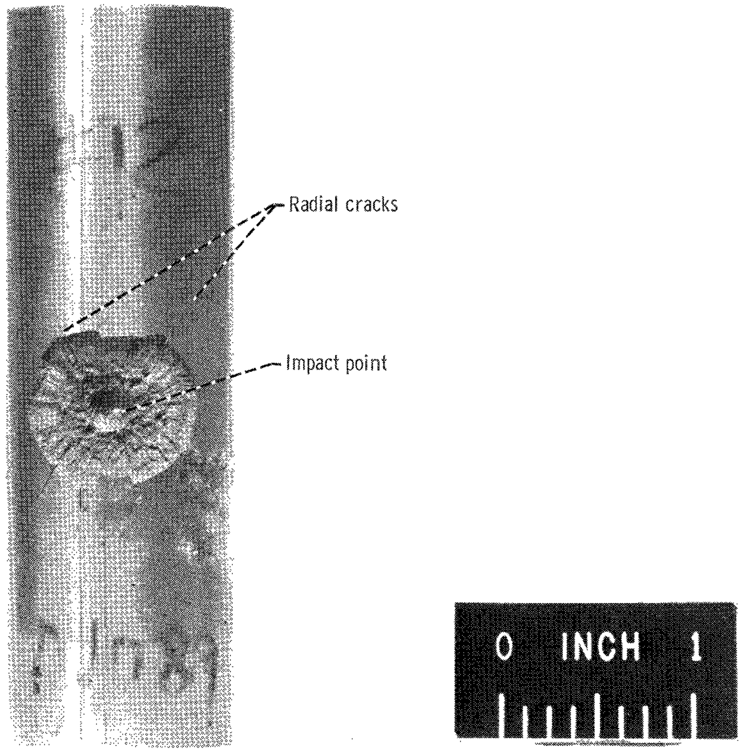


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Figure 6. - Mesh-reinforced beryllium-armored tube after impact (target 2). Test conditions: projectile, 3/32-inch-diameter pyrex sphere; impact velocity, 23 600 feet per second; target temperature, 1300° F.

External Damage

Compartment reinforcement. - The results of the impact performed on the compartmented tube are shown in figure 5. The impact occurred very close to one of the stainless-steel spacers, and the armor cracked throughout its length at the interfaces between the stainless-steel spacers and the beryllium armor. The stainless-steel liner tube was not perforated, and the inner surface of the tube was dimpled under the point of impact. Several beryllium segments were dislodged from their stainless-steel compartments near the end of the target, and those nearer the impact point were cracked but not detached from the spacers. The extensive cracking damage that occurred along the interfaces between the beryllium segments and the stainless-steel spacers is indicative of low bond strengths and the inability of the target to accommodate deformation. The compartment method of reinforcement did not localize the cracking damage within the impacted compartment.

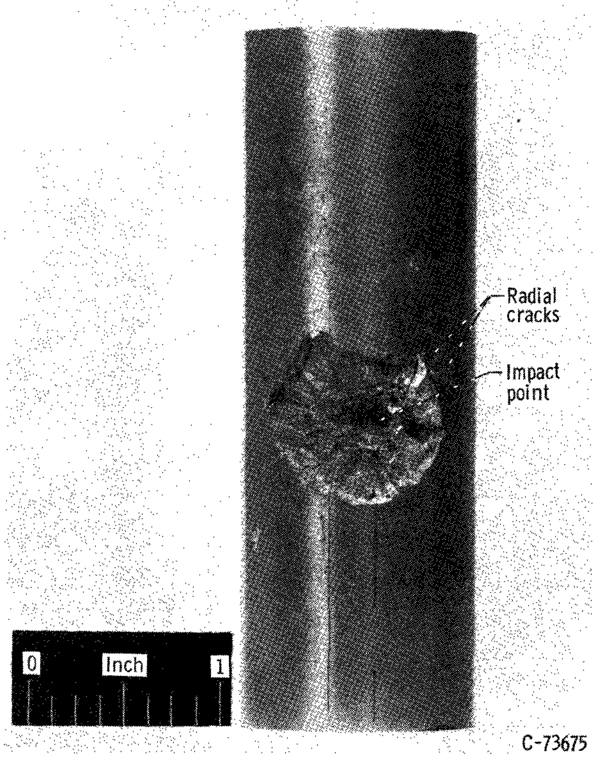


Figure 7. - Fiber-reinforced beryllium-armored tube after impact (target 3). Test conditions: projectile, 3/32-inch-diameter pyrex sphere; impact velocity, 24 000 feet per second; target temperature, 1300° F.

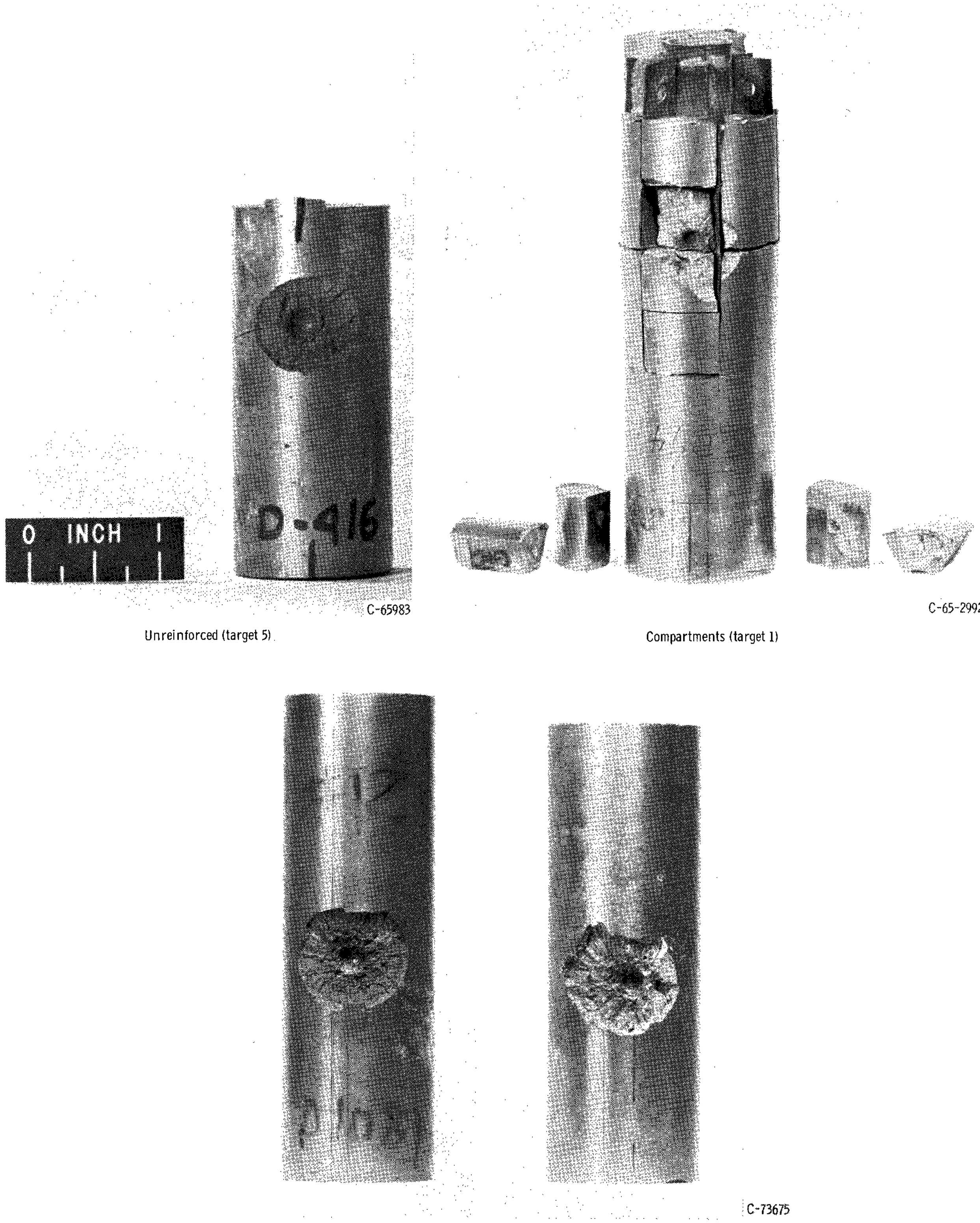
Wire-mesh reinforcement. - Figure 6 illustrates the results of impacts into the mesh-reinforced targets. The impact by the 3/32-inch-diameter spherical projectile resulted in a characteristic front-surface spall surrounding the impact point (i.e., ref. 4) with many radial cracks extending into the armor material beyond the spalled area. The tube was dimpled under the point of impact but was not perforated.

Fiber reinforcement. - The fiber-reinforced target is shown after impact in figure 7. The crater has the same general features and characteristics of beryllium impacts seen on the previous target. The liner tube was not perforated and was only slightly dimpled under the point of impact.

Comparisons. - Figure 8 shows a comparison of the unreinforced-beryllium-armored tube from reference 4 and the reinforced-beryllium-armored tubes tested in this investigation. As indicated previously, all targets were comparable in dimensions and were tested under nominally the same impact conditions. Hence, direct qualitative comparisons can be made.

A front-surface spalled area and radial cracks appeared on the target shown in figure 7. The compartmented design, however, had the most extensive armor loss and cracking damage in comparison with the unreinforced armor. The mesh and fiber reinforcements did not significantly reduce or limit the external cracking damage. Each of the four armor configurations prevented the 3/32-inch-diameter Pyrex sphere from perforating the internal liner, and all the targets were dimpled on the inner surface of the tube under the point of impact.

Double impact. - A fiber-reinforced target was impacted twice to determine if repeated impacts would result in removal of large segments of the armor cracked by the first impact. On the particular target tested, the second impact was made approximately 90° from the first impact in the same plane. Figure 9 shows both impacts and the condition of the armor between the craters. Large segments of the armor were not lost, and the increase in cracking damage was not appreciable. The cracked area around the second crater was slightly larger than that around the first crater, as can be seen from a



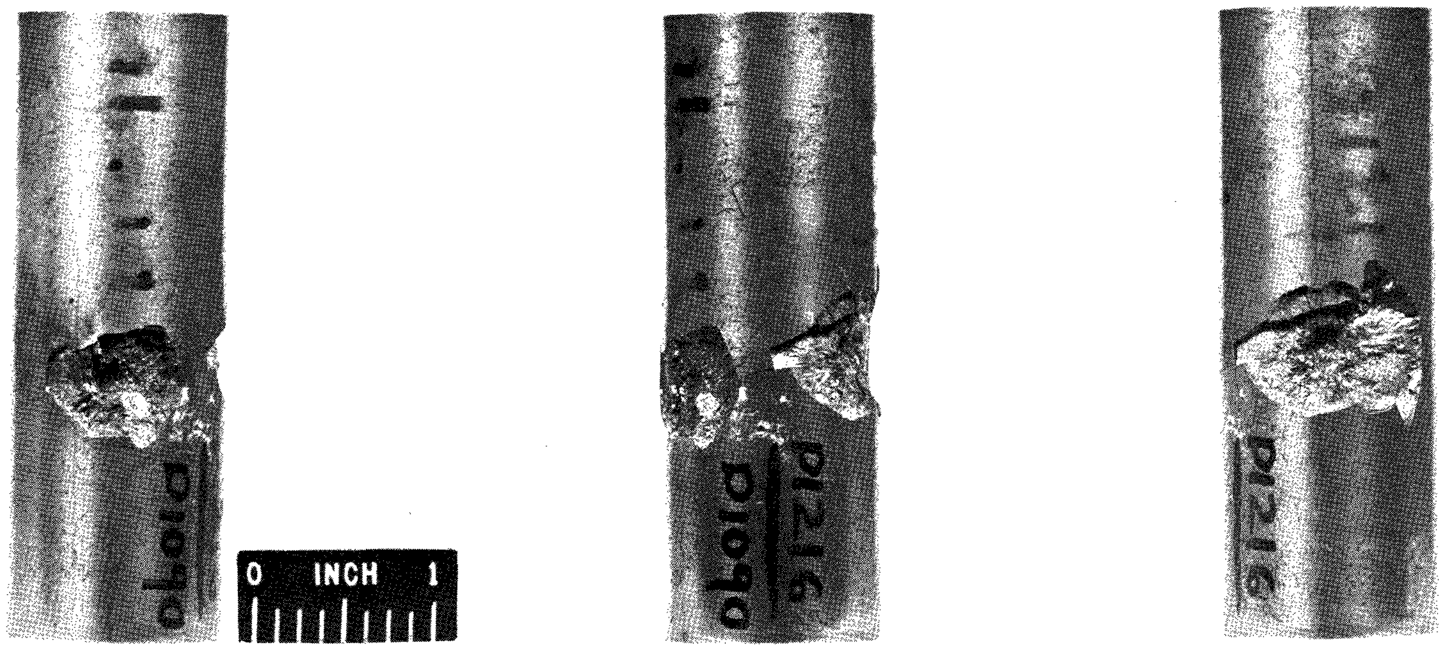
Unreinforced (target 5)

Compartments (target 1)

Concentric shells of mesh
(target 2)

Uniformly dispersed fibers
(target 3)

Figure 8. - Comparison of impact damage on tubes armored with unreinforced and reinforced beryllium. Nominal impact conditions: projectile, 3/32-inch-diameter Pyrex sphere; impact velocity, 24 000 feet per second; target temperature, 1300° F.



C-65-2995

First impact

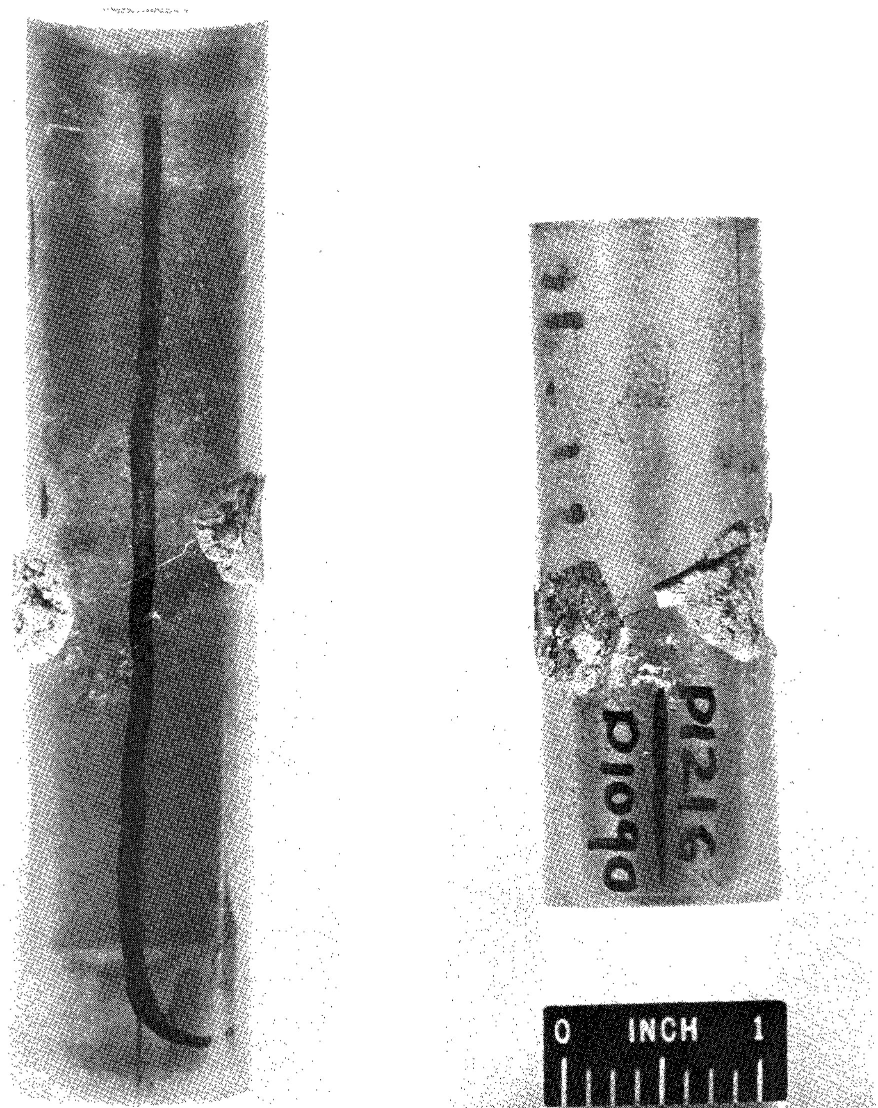
C-65-2994

View of both impacts

C-65-2996

Second impact

Figure 9. - Fiber-reinforced beryllium armored tube after two impacts. Test conditions (each impact): 3/32-inch Pyrex sphere; nominal impact velocity, 24 000 feet per second; target temperature, 1300 F.



Target 6 C-73099

Target 4 C-65-2994

Unreinforced

Fiber reinforced

Figure 10. - Unreinforced and fiber-reinforced beryllium tubes after two impacts. Test conditions: 3/32-inch-diameter Pyrex sphere; nominal impact velocity, 24 000 feet per second; target temperature, 1300° F.

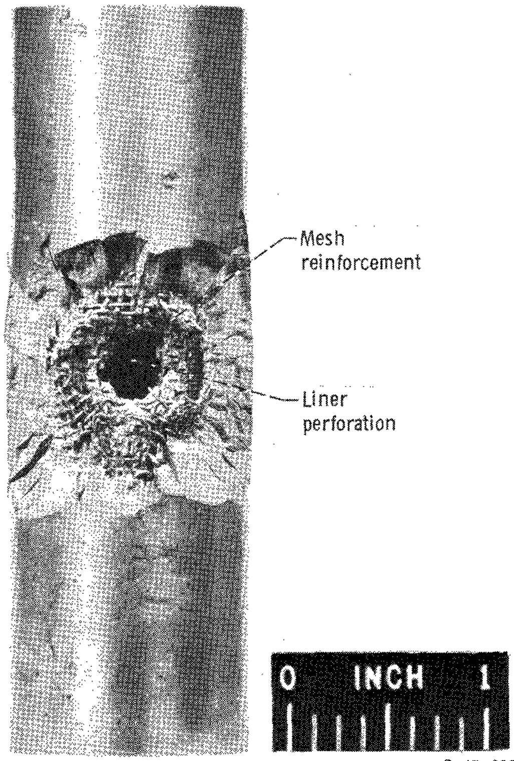


Figure 11. - Mesh-reinforced beryllium-armored tube after impact by an aluminum disk. Test conditions: projectile, ~0.1-gram aluminum disk; impact velocity, 20 500 feet per second; target temperature, 1300° F.

comparison with figure 8. Neither of the impacts, however, perforated the liner tube, and only internal dimples were visible on the inside surface of the tube.

Figure 10 shows a comparison of an unreinforced-beryllium-armored tube (ref. 4) after two impacts and target 4 of this investigation. As shown in table I (p. 6), the unreinforced target was impacted at approximately the same velocity but at a greater impact angle. Also, the wall thickness of the liner tube for the unreinforced target was 0.010 inch thick, while all targets tested in this investigation had 0.028-inch-thick liners; however, the gross damage aspects of the two targets can be compared.

Neither the fiber-reinforced nor the unreinforced targets lost armor from the combined effect of the two impacts. The liner tubes were not perforated on either of the targets, and only dimples appeared on the inner surface of the liner under the points of impact. A crack connecting the two craters was observed on both of the targets.

High-energy impact. - During the experiments one of the targets with mesh-reinforced armor was inadvertently impacted with a piece of the aluminum shear disk (fig. 1, p. 3). The impact of the aluminum disk perforated the liner tube and caused the massive damage shown in figure 11. The steel-mesh reinforcement shell can be clearly seen in the impact crater. The velocity of the disk was measured at 20 500 feet per second, and its mass was estimated to be approximately 0.1 gram. The temperature of the target at the time of impact was 1300° F. The aluminum disk had roughly four times the kinetic energy of the 3/32-inch-diameter Pyrex spheres used in the balance of the experiments, and the greater portion of damage was confined to the outer shell of armor.

Damage Factors

Although the intended purpose of the beryllium reinforcements was to limit the cracking and spalling damage, information concerning the critical-damage factors of crater depth and liner dimple height can also be obtained from the impact tests. For

TABLE II. - COMPARISON OF TARGETS AFTER IMPACT

Target	Armor configuration	Armor weight, lb/in.	Normalized penetration depth, P^*, in.	Ratio of dimple height to tube inside diameter, h/D
1	Compartmented	0.0772	0.179	0.241
2	Mesh reinforced	.0896	.189	.252
3	Fiber reinforced	.0812	.182	.258
5	Unreinforced (ref. 4)	.0688	.200	.268

lined tubes, such as those considered herein, a design damage criterion for armor thickness is likely to be the ratio of dimple height to tube inside diameter.

Given in table II are the results of the comparisons of the crater depth and the ratio of liner dimple height to inner diameter for the compartmented, wire mesh, and filament-reinforced targets, and an unreinforced target reported in reference 4. Also listed in the table are the target armor weights in pounds per inch of length obtained from the actual physical measurements of each target. Comparison of the depth of penetration into the various targets tested herein was accomplished by normalizing the measured crater depth to the reference impact velocity of 24 000 feet per second normal to the target surface in order to permit direct comparison. According to the equation reported in reference 4, the normalized penetration depth P^* is

$$P^* = P\left(\frac{V^*}{V \cos \lambda}\right)^{2/3} \tag{1}$$

where P is the measured penetration depth, V^* is the reference velocity of 24 000 feet per second, V is the measured impact velocity, and λ is the impact angle. No attempt was made to normalize the liner dimple height ratio, since the empirical variation with velocity is currently uncertain.

As can be seen from the normalized penetration depths listed in table II, the reinforced targets were penetrated to a somewhat lesser extent than the unreinforced target. Significant differences in liner dimple height ratio, however, do not seem to exist. The measured differences are believed to be well within the variations possible due to experimental error and differences in armor homogeneity and liner-armor bond.

Comparison of the weight per unit length of the reinforced armor to that of the unreinforced armor showed the compartmented, mesh, and fiber configurations to be heavier than the unreinforced configuration by 13, 30, and 18 percent, respectively. Therefore, in view of this weight increase for a given thickness, the reinforcement approaches considered in this investigation do not appear to offer any advantage.

SUMMARY OF RESULTS

The hypervelocity impact experiments on three types of reinforced-beryllium-armored stainless-steel tubes yielded the following results:

(1) Compartmented beryllium armor did not localize the cracking damage to within the impacted compartments. In addition, a tendency to dislodge segments from other compartments adjacent to the impacted compartment was prevalent.

(2) Mesh- and fiber-reinforced beryllium armor had little apparent effect on reducing observable spall and external cracking damage when compared with a comparable unreinforced target.

(3) Two separate impacts in close proximity on a fiber-reinforced tube did not result in any dislodging of cracked armor fragments. This behavior was consistent with an unreinforced beryllium target tested under similar multiple impact conditions.

(4) The normalized penetration depths were somewhat lower in the reinforced targets than in the unreinforced targets, but no significant differences in liner dimple height occurred.

(5) Both cracking damage and liner dimple height were not decreased appreciably through the use of the three types of beryllium armor reinforcements tested. Also, since the reinforcements resulted in an increased armor weight for a given thickness, the approaches considered did not appear to offer any advantage.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 11, 1966.

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